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Adjuvant effects on evaporation time and wetted area of droplets

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Abstract. *Appropriate adjuvant selection for pesticide applications is central to improve spray performances on waxy leaves and to reduce off-target losses. Evaporation and deposition patterns of 500 µm sessile droplets with five classes of adjuvants on five different waxy plants were investigated. Droplets generated with a single droplet generator were deposited on target leaves placed in a controlled environmental chamber at 60% relative humidity and 25ºC temperature. Adjuvants tested were two types of oil-based Crop Oil Concentrate (COC) and Modified Vegetable Oil (MSO), two types of surfactant Nonionic Surfactant (NIS) and Silicone Surfactant, and a type of mixture Oil Surfactant Blend (OSB), plus the water-only droplets for comparison purposes. The Silicone Surfactant was removed from the test because its various properties were inconsistent with time. The five waxy plants were difficult-to-wet with the water contact angle greater than 90º. The single water-*

only droplets did not spread with time and formed extremely tiny wetted areas on the leaf surface. The addition of the adjuvant to the spray solution significantly reduced the contact angle and increased the wetted area, but the change varied with the plant specie and the adjuvant class. In general, the MSO and NIS had obvious effects on enhancing droplet spread and maintaining the droplet in solution on the waxy leaf surface. The residual pattern of droplets after evaporation was formed with "coffee ring". Droplets with oil-based adjuvants had more uniform residual pattern than the droplet with the surfactant adjuvant. Results of this study demonstrated that selection of the appropriate class of adjuvants can significantly influence deposit formation on the waxy plants leading to effectiveness of agrochemicals.

Keywords. Contact angle; Droplet spread; Surfactant; Oil-based adjuvant; Residual pattern; Waxy plant

Introduction

All plant surfaces are coated by the thin cuticle or cuticular membrane, an important interface to protect themselves from outside environment (Wang et al, 2007; Koch et al, 2008). Characteristics of leaf surfaces of plants play an important role in the spray performances of agrochemicals (Beattie et al, 2002; Bhushan et al, 2008). A leaf surface is considered easy-to-wet if the contact angle between the leaf surface and the droplet on the leaf is less than 90º. Also, generally rougher surfaces of the easy-to-wet leaves are engaged in smaller contact angles. However, the surface roughness will increase the contact angle for the difficult-to-wet leaf surfaces with the contact angle greater than 90º (Cape, 1983; Bhushan et al, 2008). A surface is superhydrophobic if the water contact angle is above 150º (Bhushan et al, 2008). The leaf surface covered with epicuticular waxes usually presented hydrophobic characteristics (Holder, 2007). The main forms of the epicuticular waxes on the leaf surface are crystalline and amorphous (Wang et al, 2007). The composition of the waxes on leaves influences the leaf surface hydrophobicity. In addition, the surface is more water-repellant when crystalline waxes are present on the leaf surface (Beattie et al, 2002; Wang et al, 2007; Holloway et al., 2000; Smith et al., 2000).

The wettability of the leaf surface can be considered as an important factor influencing the efficiency in agrochemical application (Beattie et al, 2002; Liu, 2004; Liu et al., 1997). The epicuticular waxes on the difficult-to-wet plant leaves are the primary barrier for the deposition, retention, spreading and penetration of the droplets of agrochemical spray on the plant. Adjuvants can overcome this barrier and enhance the deposition, spread, penetration and uptake of pesticides (Gaskin et al., 2000; Hess et al., 2000; Kudsk et al., 2007; Ramsey et al., 2005 and 2006). Some of the most widely used adjuvants include surfactants, oils and ammonium salts (Wang et al., 2007; Hazen, 2000; Penner, 2000). Surfactants are the most widely used adjuvants in agrochemical applications. They help increase the wetted coverage of agrochemicals on leaf surface and promote foliar uptake (Wang et al., 2007; Hess et al., 2000; Liu, 2004; Ryckaert et al., 2007). The surfactant concentration can also influence the efficacy of agrochemical application. Increasing surfactant concentration from 0.01 to 1% will promote the foliar uptake of pesticides, but can produce negative effect on pesticide uptake when some surfactant concentration is above a critical value (Wang et al., 2007).

Spray adjuvants are usually categorized into two groups: activator adjuvants and special-purpose or utility adjuvants. Special purpose adjuvants can modify the physical characteristics of the spray solution (Hazen, 2000), including compatibilization, buffering, defoaming agent, deposition aid, and drift reduction. Activators adjuvants can enhance the biological efficacy of the chemical (Hazen, 2000), including surfactants, oils and nitrogen-based fertilizers. Surfactants primarily lower the surface tension between the spray droplet and the leaf surface and increase the coverage of the droplet. Surfactants include nonionic, anionic, cationic, organosilicones and silicones. Oil-based adjuvants are help to promote the penetration of chemical spray through a plant's waxy cuticle. The three types of oil-based adjuvants include crop oils, crop oil concentrates (COC), and vegetable oil concentrates (MSO). Nitrogen-based fertilizers can enhance the activity of chemicals.

Adjuvants can improve efficacy levels of pesticides in several ways. They enhance the droplet spread on leaf surface leading to higher wetting coverage, and they help the droplets carrying chemicals remain in solution longer periods allowing more time for the penetration and absorption of the pesticides into plants. Although a wide variety of adjuvants have been shown to improve erformance of pesticides sprayed, there is little quantitative information documenting relative effectiveness of different classes of adjuvants as spreader and humectants.

Generally pesticides are more effective if they are sprayed on the target plant uniformly and the area covered with pesticides is maximized. A coffee droplet deposited on a paper retains “coffee ring” at post-evaporation because of triple phase line (pinned line) (Deegan et al., 1997). The residual pattern of the droplets with alkyl polyoxyethylene surfactant presented “ring islands” at lower concentration of surfactant and “solid ring” of surfactant remain at higher concentrations on a mildly hydrophilic substrate (Pierce et al., 2008).

Some adjuvants are designed to perform several functions, including spreading, wetting and also acting as humectants to reduce the evaporation rate. The adjuvant used as humectants perform resisting droplets of pesticides drying on leaf surfaces, since penetration and absorption of pesticide active ingredients into plants is slow or ceases completely when droplets transform from liquid form to dry residual matter on leaves (Ramsey et al., 2005).

The wettability of the leaf surface is an important factor in achieving maximum efficacy from pesticides applied. The spread area (wetted area) of a droplet on the leaf surface may, for some pesticides, be directly correlated with the efficacy that may be achieved from that pesticide. Poor efficacy may result if a droplet carrying the pesticide active ingredients does not spread well after it lands on the leaf surface. It is not only because the coverage of droplets on the surfaces of the difficult-to-wet plants is low, but also majority of spray droplets easily roll off from the leaf surfaces in different incline direction in the field.

For systemic pesticides, the application efficiency can be improved by maximizing spray coverage and evaporation time of droplets on targets. Maximum droplet spreading leads to maximum coverage, and maximum evaporation time gives plant tissues sufficient time to absorb active ingredients.

Knowledge of the interaction of the target plant and the type of adjuvant contained in the spray mixture is essential for success of pesticide application in agriculture. The objective of this research was to determine effectiveness of five representative types of adjuvants in contact angle, wetted area, evaporation time and residual patterns of droplets after they reach surfaces of waxy plants.

Material and methods

Tests were conducted with five different waxy plants, as listed in Table 1. These plants were *Kalanchoe serrata*), (*Pelargonium peltatum*), (*Begonia sanguinea*), (*Begonia Echinosepala Var. Elongatifolia*) and (*Pelargonium Stenopetalum*). They were planted in 4-liter pots and grown in a greenhouse. The ambient temperature was controlled in the range from 25 to 30ºC. The plants were watered automatically once a day to the point that the substrate was saturated. The leaf thickness varied with the plant specie. The experiment started at three months after the plants were transplanted and lasted two months. Samples of 2 cm by 2 cm were cut from fresh leaves and were placed securely onto a glass plate using double-sided adhesive tape. Later, a droplet containing a given type of adjuvants was deposited on the adaxial surface of leaf samples. Each treatment used five samples representing five replications.

Adjuvants with five different formulations were selected for the test. They were widely used adjuvants including two oil-based adjuvants (Crop Oil Concentrate (COC) and Modified Vegetable Oil (MSO)), two surfactant adjuvants (Nonionic Surfactant (NIS) and Silicone Surfactants), and a mixture of oil-based and adjuvant Oil surfactant blend (OSB). The principal functioning agents of the adjuvants and the formulated concentration with water were described in table 2. The adjuvants were formulated by WILBUR-ELLIS Company (San Francisco, CA, USA), and were mixed with distilled water at the concentration of the manufacturer's recommendation (Table 2). For comparison purposes, tests also included treatments of droplets containing distilled water only. Tests with Silicone-based surfactants were discontinued after the evidence was found that their spreading was inconsistent with time. The sessile droplet diameter of 500 µm was chosen for the experiments.

The apparatus used in this study was designed to capture photographic images from two settings: top view (Fig. 1a), and side view (Fig. 1b). Sequential images of a droplet taken from the top view were used to assess spreading and evaporation rates of droplets containing various adjuvants. The sequential images from the side view were used to determine the changes in the contact angle of the droplet in time. The images of droplets were taken with 40 magnifications.

The experimental system used for the top view of droplets included a droplet dispensing component, an environmental control chamber, and an image acquisition component (Fig. 1a). The droplet dispensing component was mainly a droplet generator (Model 2405, EFD Inc., East Providence, RI) with a 3 mL barrel-piston micro-syringe and a chamfered tip with an inside diameter of 10 mm. The environmental control component consisted of an environment control chamber, an air mixing chamber, a humidifier, a dehumidifier, a micro data logger, two humidity-temperature sensors and a portable computer. A target object (leaf sample) was placed on a movable platform inside the environment control chamber. The air entering the environment control chamber from the air mixing chamber satisfied the conditions set for relative humidity and temperature. The image acquisition component contained a stereo microscope (Olympus, Model SZX12, Japan), an INSIGHT FIREWIRE© Color Mosaic digital camera (Model 18.2, Diagnostic instruments Inc., Sterling Heights, MI) in vertical position and an image acquisition computer. Detailed information about the apparatus was given by Zhu et al., (2008).

The experimental system used for the side view of droplets was basically the same as the system for the top view, except the humidity control chamber was not used and the stereo microscope with the camera was oriented for taking droplet images horizontally (Fig. 1b).

The contact angle of a water droplet on a leaf surface can be used to illustrate the wettability of the plant. A surface is considered "wettable" if the water contact angle is less than 90º, and "non-wettable" surface if the water contact angle is greater than 90º (Cape, 1983; Bhushan et al., 2008). The contact angle of a droplet on leaf surfaces is commonly measured by the tangent method described by Zisman (1964). This method assumes that the droplet is deposited on a flat smooth surface. However, leaf surfaces are usually convoluted. Thus, it is difficult to determine the point of intersection between the droplet contact profile and the leaf surface. Consequently, the measurement of contact angle of droplets on leaves with the tangent method will result in significant errors.

For this study, it was assumed that the shape deformation of droplets on the leaf surfaces by gravity could be ignored. The shape of the droplet on the leaf surface was considered as the segment of a sphere (Figs. 2a and 2b). The contact angle (θ) was determined with the following equation by measuring the contact width (S) of the droplet on the leaf surface and the height (H) of the droplet (Fig. 3).

$$\theta = \begin{cases} \arctan \dfrac{1}{\dfrac{S}{4H} - \dfrac{H}{S}}, \text{ if } R \geq H \\ 180° + \arctan \dfrac{1}{\dfrac{S}{4H} - \dfrac{H}{S}}, \text{ if } R < H \end{cases} \quad (1)$$

Where, *R* is the radius of the sphere, and is calculated with the equation,

$$R = \frac{S^2}{8H} + \frac{H}{2} \quad (2)$$

For example, the measured values of *S* and *H* for this droplet shown in Figure 2 were 336 μm and 357 μm, respectively. The radius R of the droplet was calculated as 218 μm which perfectly fit to outline of the droplet (Fig. 2b). The contact angle was then calculated as 124 º for the example.

The "wetted area", defined as the maximal contact area of a droplet on a leaf surface after deposition, was obtained with the Polygonal Hand-trace feature of Image-Pro Plus software (Version 6.1, Media cybernetics, Bethesda, MD, USA) to trace the marked outline of the deposit contact area on the leaf surface.

The sequential images taken by the camera was used to record the droplet spread and evaporation processes with the time after it was deposited on a leaf surface. The first image was taken when the droplet was deposited on the leaf surface and the last image was taken when the droplet completely evaporated. The evaporation time of a droplet was calculated by the number of sequential images multiplied by the interval time between two sequential images. The interval time was set at 2 seconds in this study.

Sessile droplets of 500 μm were selected for the test. With this size, the droplet generator was able to produce constant-size droplets while the size was small enough to avoid the shape deformation for the contact angle measurement. During this study, the relative humidity and the temperature were set at 60% and 25ºC, respectively. Each treatment was repeated for five times.

Data for wetted area and evaporation time from replicated samples were analyzed with the Duncan method of the version 3.8 (Poly Software International, Inc., Pearl River, NY). All differences were determined at the 0.05 level of significance. An integrated index λ was used to evaluate the ability of the droplet spreading and resisting evaporation, which were the product of the evaporation time *T* and the wetted area *A* of a droplet on a leaf surface, $\lambda = T \cdot A$.

Results and discussion

Contact angle

Table 3 shows the contact angle of 500 μm droplets with four types of adjuvants (COC, MSO, NIS and OSB) and a water-only solution on leaves of five waxy (glassy) plants (*K. Serrata*, *P. peltatum*, *B. Sanguinea*, *B. Echinosepala* and *P. Stenopetalum*). The contact angles of the water-only droplets on all five plants were greater than 90º, indicating that the leaf surfaces of all five plants were non-wettable or difficult-to-wet. Contact angles among five waxy plants were significantly different. Among the five plants with water-only droplets, *B. Echinosepala* had the lowest contact angle (91.2°) on the leaves, and *K. Serrata* had the highest contact angle (122.1°). As shown in Table 3, when any of the four adjuvants was added to the solution, the contact angle decreased noticeably as a result of lower surface tension of droplets resulting from addition of adjuvants to the spray solution. Among the adjuvants tested, MSO was the most effective and COC was the least effective adjuvant in reducing contact angle of droplets on waxy plant leaves. These two oil-based adjuvants presented markedly difference in decreasing contact angle. Compared to the water-only droplet, the contact angle of the droplets with the MSO decreased by 79.3%, 57.1%, 56.9%, 54.9% and 52.9%, on the *K. Serrata*, *B. Echinosepala*, *P. Peltatum*, *B. Sanguinea* and *P. Stenopetalum*, respectively. The contact angle of droplets on *K. Serrata* was reduced the most among the five plants when any of the five adjuvants was mixed with the spray solution. The contact angle on *K. Serrata* was the highest for the water droplet among the five plants, but was the lowest for the droplet with each adjuvant. Therefore, the contact angle was greatly reduced when the adjuvant was added into the spray solution.

Wetted area

The average wetted area of water droplets on five waxy plants ranged from 0.114 to 0.275 mm^2 (Table 4). Corresponding to the lowest contact angle, the *K. serrata* had the smallest wetted area of water droplets without adjuvants among the five plants. The wetted area increased significantly when adjuvants were added to the solution. The adjuvants MSO and NIS showed significantly greater effectiveness in droplet spreading than other two adjuvants COC and OSB. The performances of the two oil-based adjuvants (MSO and COC) on the droplet spread characteristics were greatly different. The MSO had much stronger spread ability of droplets than the COC, even though the solution concentration of the COC was twice as much as that of the MSO. The mixture of oil and surfactant OSB had the least effect on spreading ability of droplets on all five plants. One reason for this may be the fact that the recommended concentration of this adjuvant in the mixture was very low. MSO is generated from renewable resources, being a kind of modified vegetable (seed) oil. On the contrary, COC is the paraffin based petroleum oil. Hence, oil-based adjuvants made from the vegetable (seed) oil had greater spreading capabilities than the adjuvants from the petroleum oil.

Compared to water-only solution, adjuvants MSO and NIS increased wetted area on *K. Serrata* leaves by 675% and 639%, respectively. In general, the adjuvants increased spreading area more notably on *K. Serrata* and *B. Echinosepala* than on other three plants. The wetted area of droplets with MSO adjuvant on *K. Serrata* was 28.6% larger than that on *B. Echinosepala*. Inversely, the wetted area of droplets with OSB adjuvant on *K. Serrata* was 41.3% lower than that on *B. Echinosepala*.

Figure 4 shows the wetted area per droplet volume of the 500 μm droplets with and without four adjuvants on the five different plant leaves. The wetted area per droplet volume on the five plant leaves ranged from 7.2 to 9.0 mm^2/mm^3 with COC, from 7.5 to 13.5 mm^2/mm^3 with MSO, from 8.0 to 12.9 mm^2/mm^3 with NIS, from 4.8 to 8.2 mm^2/mm^3 with OSB, and from 1.7 to 4.2 mm^2/mm^3 with water-only, respectively. Apparently, droplets with adjuvants increased wetted area per droplet volume while the increase degree varied with the type of adjuvants. MSO and NIS had greater wetted area per droplet volume on all five plant leaves than COC and OSB. Hence, choosing proper adjuvants for particular plants is necessary to obtain maximal spreading performances of spray droplets to increase spray application efficiency.

Evaporation time

The evaporation time of 500 μm droplets with four types of adjuvants and water-only solution on five different plants are presented in Table 5. In contrast to the wetted area, the evaporation time did not change greatly with the adjuvant type. Evaporation time of the droplets with adjuvants on five different plants ranged from 103.6 to 198.0 s while it ranged from 144.8 to 282.4 s without adjuvants. Compared to the water-only droplets, the average evaporation time on five waxy plants decreased only by 18.5%, 22.8%, 28.2% and 30.6%, with the COC, NIS, MSO and OSB, respectively. That is, adding the adjuvants into sprays slightly accelerated droplet evaporation after deposition on leaves. In generally, the droplet that had a greater wetted area would have higher evaporation rate on the waxy leaves. The droplets with COC remained the longest in liquid form and the droplets with OSB presented the shortest average evaporation time among the four adjuvants. The solution with a lower concentration might be less effective in droplet spread and resisting evaporation because COC had the highest concentration and OSB had the lowest concentration (Table 2).

Similarly, the evaporation time was slightly influenced by the waxy plant specie. The evaporation time of droplets on two begonia varieties (B. sanguinea and B. echinosepala) was significantly lower than that on other three plants. Compared to the water-only droplets, the average evaporation time with four adjuvants was the longest on *P. stenopetalum*, and the shortest on *B. echinosepala.* The average evaporation time of droplets with four adjuvants was 28.2% longer on *K. serrata* than that on *B. echinosepala*, even though the average wetted area on both of them was the same.

Figure 5 shows the evaporation time per droplet volume of the 500 μm droplets with and without four adjuvants on the five different plant leaves. Addition of adjuvants into solutions reduced the droplet evaporation time per droplet volume while the amount of reduction did not vary with the adjuvant type apparently.

The droplet evaporation is a complex process which is influenced by leaf surface characteristics including the composition of wax layer, heat conduction of leaf surface, aqueous translocation ability through tiny reticulate veins or stomata, and penetration ability through epicuticular wax, cuticular wax and cutin matrix.

The integrated index λ of 500 μm droplets with and without the four different adjuvants on the five different plant leaves are given in Table 6. The λ value of water-only droplets was much lower than droplets with adjuvants although water-only droplets had longer evaporation time. The λ value also varied with the adjuvant type and plant specie. The nonionic surfactant NIS and oil-based MSO adjuvant droplets had greater λ values due to higher droplet spreading and lower evaporation rates on waxy plants, especially on *K. serrata.* For example, the difference in the average λ value between the *K. serrata* and *B. sanguinea* with the same NIS adjuvant reached 40.4%. OSB had significantly lower λ value than the other adjuvants. The λ values of adjuvants associated with each type of the waxy plants varied significantly.

Due to the increased wetted area, the application efficiency of pesticides with adjuvants should be considerably increased especially for waxy plants with the water contact angle above 90º. The addition of specific adjuvant to the spray solution is a practical and readily available option applicators can take advantage of to improve effectiveness of pesticides applied. Results of this study indicate that droplets carrying a spray solution mixed with adjuvants such as oil-based adjuvants, nonionic surfactants and oil and surfactant blends, lead to better performance as a result of improved spreading and retardation of the drying rate of the droplets, especially on waxy plants. However, the difference in the application performance of the droplets was significant with the waxy plant species and the adjuvant type. In general, the oil-based MSO adjuvant and the nonionic surfactant NIS were significantly more effective in reducing the surface tension which lead to lower contact angles, increased wetting and spreading on the leaf surface (coverage) and lengthening the evaporation time of sprayed droplets.

Residual pattern of droplet

Figure 6 shows residual patterns of 500 µm droplets at post-evaporation stage on the surface of *B. sanguinea* leaf with four types of adjuvants at five replicated samples, at 60% relative humidity and 25ºC. A “coffee ring” was formed on the leaf surface after evaporation, although each residual pattern was different, such as solid ring, broken ring or islands. The residual patterns of droplets with NIS were narrow solid or broken ring, but wider ring or islands appeared with oil-based adjuvants COC and MSO. That is, the residual pattern of the droplets with oil-based adjuvant was better than with the nonionic surfactant adjuvant. The solution with the oil-based adjuvants had higher surface tension that modified the droplet spread by reducing the capillary flow of the droplets. Visually, the residuals of droplets with COC, MSO, or OSB covered relatively larger areas with more small islands or broken rings than NIS droplets (fig. 6). Obviously, the residuals covering larger areas on leaves are desirable to improve uniformity of spray deposition on leaves. Lowering the concentration of the nonionic adjuvant might allow the residual pattern to be formed with small islands distributed in the wetted area (Pierce et al., 2008). However, the droplet might not spread if the concentration is too low. Some concentrated pesticides are formulated with surfactants, but their droplet spreading was not significant due to the amount of surfactant in the formulations was very low (Yu et al., 2009).

Conclusions

The contact angle of droplets on waxy leaves of all five plants was greatly reduced when either adjuvant COC, MSO, INS, or OSB was mixed with water to form spray solutions.

The wetted area on leaves of different species increased significantly when adjuvants were used in the solutions. The adjuvants MSO and NIS had significantly greater effectiveness in droplet spreading than other two adjuvants COC and OSB. The adjuvants increased spreading area more notably on *K. Serrata* and *B. Echinosepala* than on other three plants.

Compared to water-only solution, adjuvants MSO and NIS increased wetted area on *K. Serrata* leaves by 675% and 639%, respectively.

The spreading performance of two oil-based adjuvants MSO and COC on waxy leaves were significantly different. Droplets with MSO had much stronger spread ability than the COC.

Evaporation time of droplets on leaves of different species did not change greatly with the adjuvant type. With adjuvants the 500 µm droplets had evaporation time ranging from 103.6 to 198.0 s while without adjuvants the range was from 144.8 to 282.4 s.

Residual patterns on leaf surfaces were formed as the “coffee ring” after evaporation of droplets with the adjuvant of any type. The residual pattern of droplets with COC was formed with small islands instead of a solid ring.

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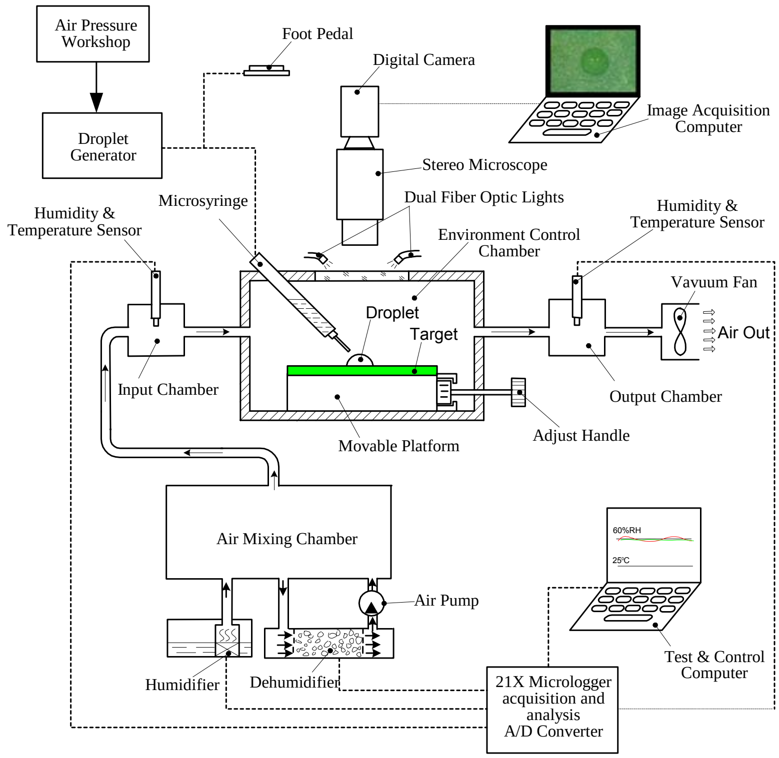


Figure 1. Experimental system to determine droplet evaporation and spreading on waxy leaves in an environmentally-controlled chamber

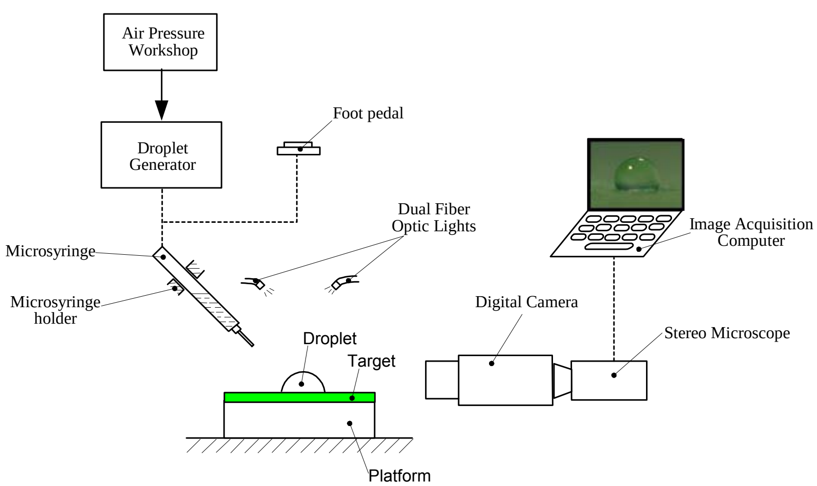


Figure 2. Experimental system to determine contact angle of droplets on waxy leaves.

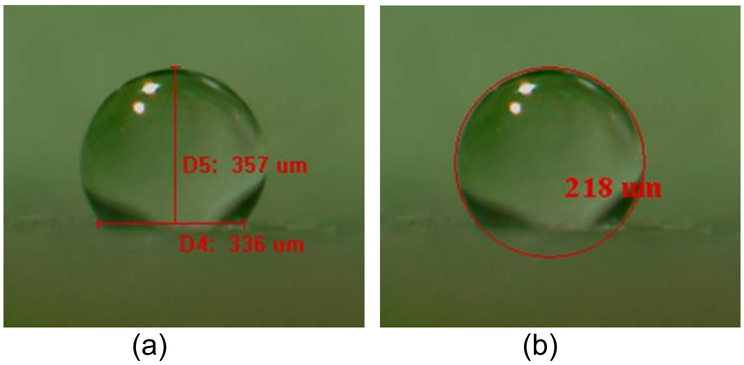


Figure 2. A 500 µm water-only droplet deposited on a leaf surface of *K. serrata*. the (a) measurement of contact length and height of the droplet on the leaf surface, (b) calculated circle that coincided with the outline of the droplet.

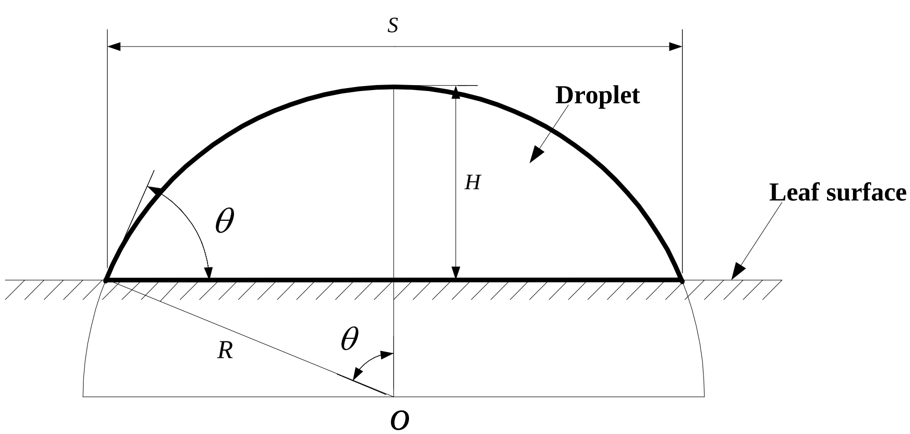


Figure 3 Geometry to determine the contact angle of a droplet on leaf surfaces.

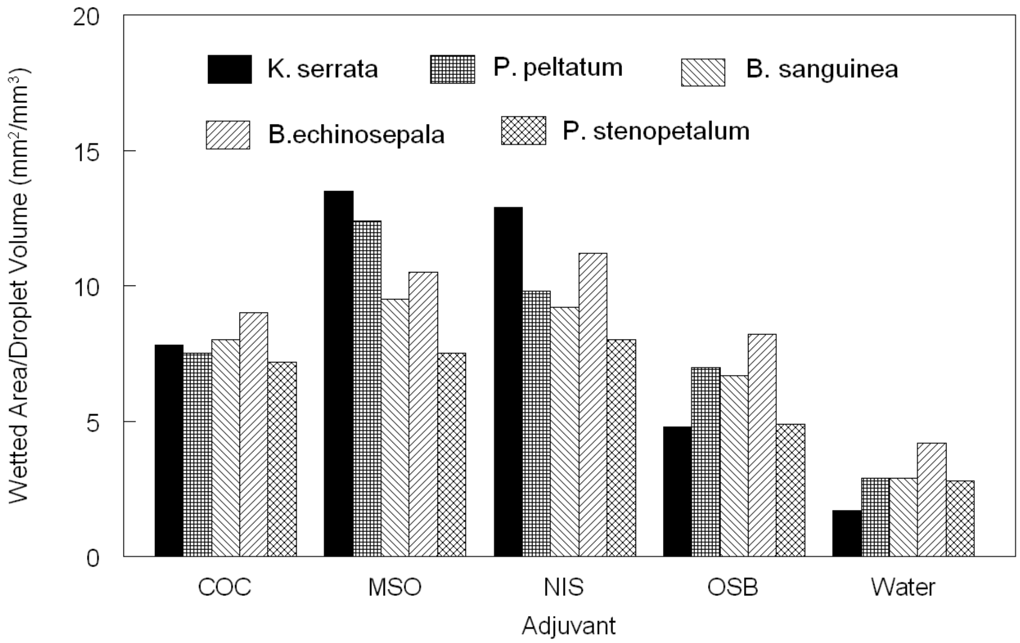


Figure 4. Wetted area per droplet volume of 500 µm droplets with and without adjuvants on five different waxy plants

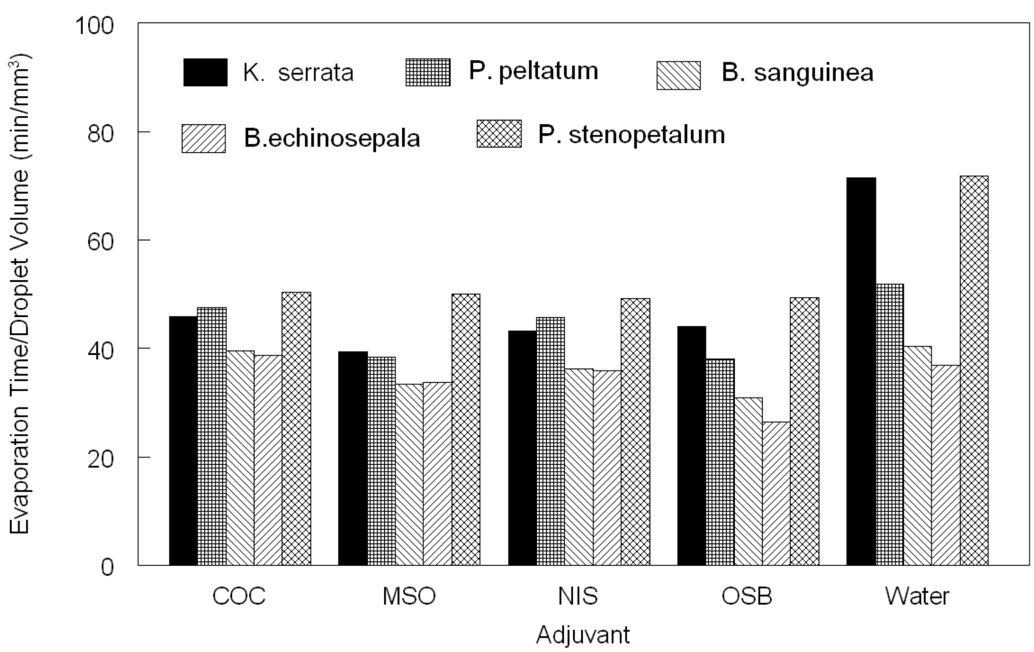
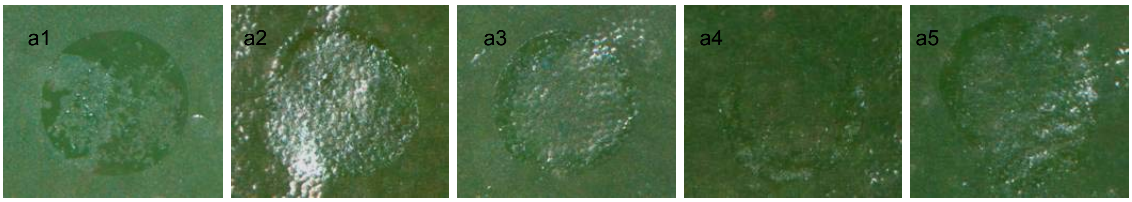
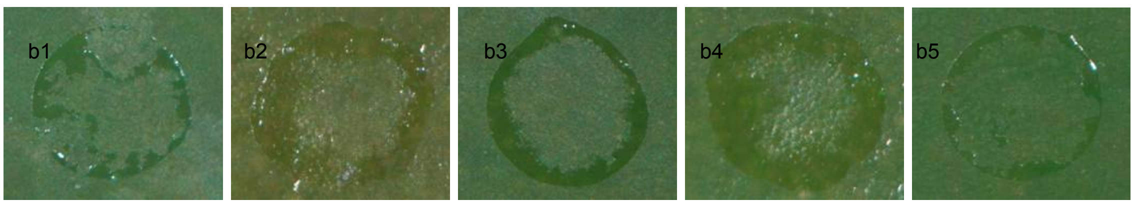


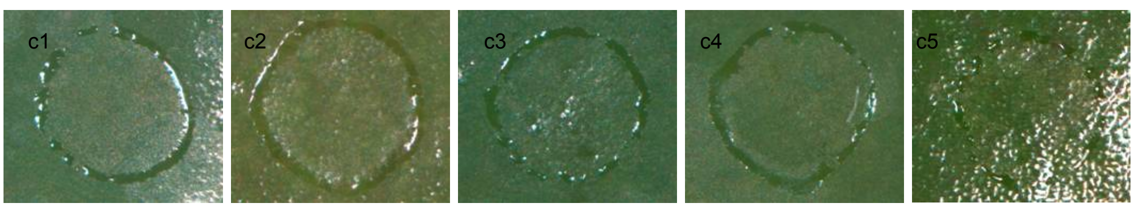
Figure 5. Evaporation time per droplet volume of 500 µm droplets with and without adjuvants on five different waxy plants



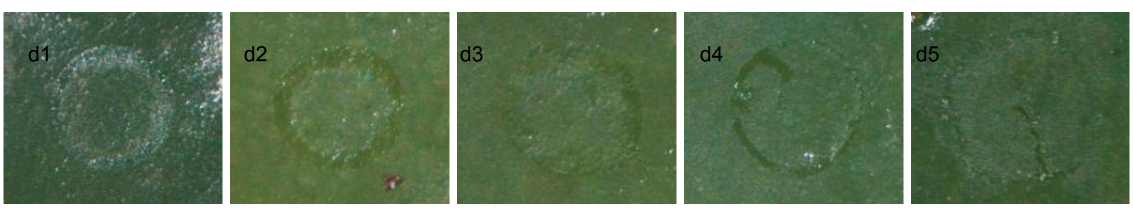
a. COC



b. MSO



c. NIS



d. Oil Surfactant Blend

Figure 6 Residual patterns of 500 μm droplets post-evaporation on the leaf of *Kalanchoe Serrata* with four types of adjuvants, *Crop Oil Concentrate* (COC) (a), *Modified Vegetable Oil* (MSO) (b), *Nonionic Surfactant* (`) (c), and *Oil Surfactant Blend* (d) with five replicated samples, at 60% relative humidity and 25ºC.

Table 1. Adjuvants and their concentrations in water used in the tests

Adjuvant	Principal functioning agents	Concentration (% v/v)	Surface tension (dynes/cm)
Crop Oil Concentrate (COC)	Paraffin base petroleum oil 83%; surfactant blend 17%.	1.040	34.6
Modified Vegetable Oil (MSO)	Methyl soyate, nonylphenol ethoxylate blend (surfactant content 15%)	0.521	35.4
Nonionic Surfactant (NIS)	Alkylphenol ethoxylate, butyl alcohol, dimethylpolysiloxane 90%; Constituents Ineffective as Spray Adjuvant 10%.	0.250	31.8
Oil Surfactant Blend (OSB)	Ethylated seed oil; 3-(3-hydroxypropyl)-heptamethyltrisiloxane, ethoxylated acetate; polyoxyethylene dioleate; polyol alkyl thoxylate (surfactant content 40%)	0.130	29.0
Silicone Surfactant	A mixture of 3-(3-hydroxypropyl) heptamethyltrisiloxane, ethoxylated acetate/125997-17-3, polyethylene glycol monallyl acetate/27252875, polyethylene glycol diacetate/27252831.	0.065	26.5
Water-only			72.8

Table 2. Contact angle (º) of 500 µm droplets with and without adjuvants on five different waxy plants. Standard deviations are presented in parentheses. Means in a column followed by a different letter are significantly different ($p<0.05$).

Adjuvant	K. serrata	P. peltatum	B. sanguinea	B. echinosepala	P. stenopetalum
COC	37.4 ^{b} (2.8)	57.7 ^{b} (7.3)	58.2 ^{b} (3.7)	43.2 ^{b} (11.3)	53.9 ^{b} (4.9)
MSO	25.3^{c} (3.5)	42.9 ^{c} (6.5)	49.7 ^{c} (1.8)	39.1 ^{b} (8.2)	46.5 ^{b} (6.9)
NIS	33.9 ^{b} (6.3)	48.6 ^{bc} (8.0)	54.2 ^{bc} (3.3)	45.2 ^{b} (8.9)	50.9 ^{b} (4.6)
OSB	37.7 ^{b} (6.2)	43.5 ^{c} (6.8)	51.5 ^{c} (4.0)	43.5 ^{b} (7.7)	50.6 ^{b} (9.5)
Water-only	122.1 ^{a} (11.3)	99.6 ^{a} (2.5)	110.2 ^{a} (4.5)	91.2 ^{a} (15.3)	98.8 ^{a} (6.4)

Table 3. Wetted area (mm^2) of 500 µm droplets with and without adjuvants on five different waxy plants . Standard deviations are presented in parentheses. Means in a column followed by a different letter are significantly different ($p<0.05$).

Adjuvant	K. serrata	P. peltatum	B. sanguinea	B. echinosepala	P. stenopetalum
COC	0.509 [a] (0.044)	0.491 [a] (0.072)	0.524 [ab] (0.052)	0.591 [a] (0.224)	0.471 [a] (0.164)
MSO	0.884 [b] (0.272)	0.812 [b] (0.292)	0.621 [c] (0.062)	0.687 [a] (0.176)	0.491 [a] (0.090)
NIS	0.842 [b] (0.329)	0.641 [ab] (0.081)	0.601 [bc] (0.050)	0.734 [a] (0.133)	0.526 [a] (0.088)
OSB	0.316 [ac] (0.052)	0.461 [a] (0.042)	0.439 [a] (0.092)	0.538 [a] (0.183)	0.321 [b] (0.067)
Water-only	0.114 (0.009)	0.190 (0.019)	0.189 (0.036)	0.275 (0.039)	0.185 (0.025)

Table 4. Evaporation time (s) of 500 µm droplets with and without adjuvants on five different waxy plants . Standard deviations are presented in parentheses. Means in a column followed by a different letter are significantly different ($p<0.05$).

Adjuvant	K. serrata	P. peltatum	B. sanguinea	B. echinosepala	P. stenopetalum
COC	180.0 [b] (4.0)	186.4 [b] (29.3)	155.2 [a] (16.4)	152.0 [a] (7.3)	198.0 [b] (33.0)
MSO	154.8 [c] (17.2)	150.8 [c] (17.8)	131.2 [bc] (7.3)	132.4 [b] (13.3)	196.4 [b] (15.2)
NIS	170.0 [bc] (16.4)	179.2 [bc] (24.1)	142.0 [ab] (6.8)	140.8 [ab] (5.4)	193.6 [b] (31.1)
OSB	173.2 [bc] (15.1)	149.6 [c] (10.8)	121.6 [c] (5.0)	103.6 [c] (10.5)	194.0 [b] (36.7)
Water-only	280.8 [a] (19.2)	203.2 [a] (33.5)	158.4 [a] (5.0)	144.8 [ab] (16.3)	282.4 [a] (50.0)

Table 5. Integrated index ($sec \cdot mm^2$) of 500 µm droplets with and without adjuvants on five different waxy plants.

Adjuvant	K. serrata	P. peltatum	B. sanguinea	B. echinosepala	P. stenopetalum
COC	91.6	91.5	81.3	89.8	93.3
MSO	136.8	122.4	81.5	91.0	96.4
NIS	143.1	114.9	85.3	103.3	101.8
OSB	54.7	69.0	53.4	55.7	62.3
Water-only	32.0	38.6	29.9	39.8	52.2